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ULTRAFAST POLARIZATION SWITCHING DYNAMICS IN VERTICAL-CAVITY SURFACE-EMITTING LASERS

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13. ABSTRACT *(Maximum 200 words)*
The interaction of circularly-polarized femtosecond laser pulses with commercial vertical-cavity surface-emitting lasers (VCSELs) was studied using a pump-probe configuration in connection with an autocorrelation setup for time-resolving anticipated polarization changes in the VCSEL output. In addition, extensive theoretical modeling was performed to gain greater insights into the physical bases for output polarization in VCSELs. The objective of these efforts was to determine if VCSEL output polarization could be switched on a picosecond time scale, and if the polarization of multiple elements in a VCSEL array could be externally controlled and "pinned" to a particular desired orientation. The theoretical modeling was completed. Experimental verification of the model could not be carried out because the VCSELs available at the time did not have high enough output power.

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Contents

Abstract

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Acknowledgments

The Vertical-Cavity Surface Emitting Lasers (VCSELs) used in this work were donated to the SUNY Institute of Technology by Vixel, Inc. of Longmont, Colorado. Dr. Mark Krol, currently with Corning, Inc. in Corning, New York, assisted in the design of the optical beamtrain used to make pump-probe and autocorrelation measurements. Dr. Alexander Cartwright of the SUNY Buffalo Electrical Engineering Dept. provided an alternate test set-up in his laboratory that was used in the latter portion of the project by one of his graduate students. Mr. Paul Lein, an undergraduate in the Photonics Program at the SUNY Institute of Technology, spearheaded a significant portion of our computer-interfacing efforts. The respective contributions of these individuals to this project are gratefully acknowledged.

1 Introduction

VCSELs have shown promise as an enabling technology in several commercially-relevant applications, including high-speed laser printing, compact displays, and parallel fiber communications[1]. Perhaps the most attractive feature of VCSELs in this regard is the ease with which they can be fabricated in *n x n* arrays with high process yields. Unfortunately, though such arrays can be manufactured in such a way as to demonstrate reasonably uniform threshold currents, output powers, and wavelengths across the multiple elements of the array, it has proven more difficult to insure that their polarization orientation is identical from element to element. In fact, individual VCSEL array elements, though producing nominally linear polarization, often tend to have random polarization orientations. This represents an operating disadvantage in applications requiring polarization-dependent beam steering, such as when polarizing beamsplitters or waveplates are used. Furthermore, in more exotic projected applications of VCSEL arrays, including free-space image-processing and digital optical logic, high-speed polarization switching of individual array elements would be highly desirable. Exploring the possibility of external polarization control of VCSEL arrays as well as ultrafast switching of individually-addressed array elements using femtosecond polarized control pulses has been the focus of the research described in this report.

2 Overview of Work Performed

The key project accomplishments can be summarized as follows:

- Several different types of commercially-available VCSEL devices were characterized in terms of their drive current, output power, robustness, and output polarization properties.

2 Overview of Work Performed (cont.)

- A pump-probe facility for characterizing VCSEL response to femtosecond optical pulses was constructed, tested, and refined.

- Femtosecond pulses at 780 nm were focused onto the active region of VCSELs emitting at 840 nm, and significant efforts were exerted to measure the VCSELs resulting temporal response.

- Two separate but related theoretical models of VCSEL polarization properties were developed, refined, and applied to particular operating regimes. Two papers in peer-reviewed journals and four presentations at international conferences resulted from these modeling efforts.

In the sections that follow, we review these accomplishments. Section three discusses our theoretical modeling efforts; section four briefly summarizes experimental work performed; and section five contains our conclusions.

3 Theoretical Modeling

Theoretical investigations concerning the light-vector polarization behavior of VCSELs were performed as part of this project by Prof. R. Binder at the University of Arizona. Results in these areas led to two publications in peer-reviewed journals[2,3] and were presented at several international conferences[4-7]. In particular, the following issues were addressed theoretically and investigated by means of numerical simulations of the appropriate models:

3 Theoretical Modeling (cont.)

(i) The ultrafast nonlinear optical response of uniaxially-strained semiconductor quantum wells and

(ii) the vectorial mode structure of vertical-cavity surface-emitting lasers (VCSELs).

The relationship between these two issues lies in the fact that VCSELs do not necessarily contain perfect cubic quantum wells as active material. There is evidence that in reality these quantum wells are slightly strained, a generally small effect which can have a large effect on the polarization properties of the output light field of VCSELs. A solid theoretical foundation was laid for both issues during this project, and we anticipate that future projects will allow us to combine both theories and eventually arrive at a comprehensive theoretical model of the polarization characteristics of micro-cavity lasers and LEDs.

Ultrafast Nonlinear Optical Response of Uniaxially-strained Semiconductor Quantum Wells

This first issue consists of several sub-topics, out of which the coherent femtosecond nonlinear response was the main focus of this project and required the largest amount of software development. It is based on the derivation and numerical investigation of the extended semiconductor Bloch equations including the Luttinger hamiltonian to account for strain effects and the Coulomb potential to account for linear and nonlinear excitonic effects.

From a numerical point of view, the key challenge in the solution of the equations underlying the ultrafast nonlinear optical response of uniaxially-strained semiconductor quantum wells was the evaluation of the Coulomb integrals, which are of the form of convolutions of the Coulomb potential and material functions such as the polarization and distribution functions. The integrals are two-dimensional integrals which depend on the two-dimensional vector $\mathbf{k}$.

3 Theoretical Modeling (cont.)

The resulting numerical complexity had been the reason that all conventional solutions of the semiconductor Bloch equations had previously been restricted to isotropic systems, in which the convolution integrals are essentially one-dimensional and depend only on $|\mathbf{k}|$. The successful completion of this project therefore depended on the question of whether optimized algorithms could be found to solve the anisotropic semiconductor Bloch equations.

It turned out that the community of nuclear physicists had successfully dealt with mathematically similar problems by means of Fast-Fourier-Transform (FFT) algorithms. The basic idea is to use the FFT to transform the functions to be convolved from momentum into real space, perform the product, and transform the product back via FFT to momentum space. This yields the desired convolution integral. The application of this general idea to the specific problem of the multiband semiconductor Bloch equations resulted in a large numerical code which ran on Convex as well as Cray C-90 computers. The time-integration was performed via a standard 4th-order Runge-Kutta method and, for the calculation of optical spectra, the subsequent Fourier transform from time to frequency space was performed via standard integration routines (i.e., not necessarily FFTs). A typical time-integration over several picoseconds required on the order of 10 minutes to 1 hour of Cray CPU time.

The numerical results were tested thoroughly to yield the correct behavior for the excitonic dichroism in the linear optical regime. In addition to comparisons with analytically known limiting cases (i.e., the linear regime without Coulomb interaction), the comparison with experimental results for uniaxially strained quantum wells obtained by a group at the Army Research Laboratory confirmed the correct use of the Luttinger hamiltonian and the exciton contributions to the equations-of-motion.

3 Theoretical Modeling (cont.)

As described in detail in ref. 2, very interesting results can be obtained in the single-pulse configuration for the interaction-induced polarization rotation. Here, the repulsive interaction between excitons is the main cause of the nonlinear response. Pauli-blocking and saturation effects have been found to be less dramatic.

The Vectorial Mode Structure of Vertical-cavity Surface-emitting Lasers (VCSELs)

We now turn to the topic which was designed to lay the foundation for a future application of the microscopic theories discussed above to the technology-oriented field of micro-cavity lasers and VCSELs. This work was partly motivated by the fact that the understanding of the polarization characteristics of the VCSEL output requires a detailed knowledge of the vectorial eigenmodes of the empty cavity. The understanding of the vectorial mode structure provides the proper basis in which one can expand the light field when modeling running VCSELs. This, in turn, should enable the understanding of the experimentally observed coexistence and switching between transverse modes.

One goal of this project was to provide a general as well as an approximate analytical method to analyze the modal structure of VCSELs taking into account their polarization properties. For clarity, we focused on the idealized system of cold--cavity modes, i.e., we assumed all refractive indices to be real, and, therefore, the absence of gain and absorption from the system. In the cold--cavity configuration the only information about the electromagnetic modes of VCSEL structures can be obtained from their reflectivity spectra, which was also calculated (see Ref. 2).

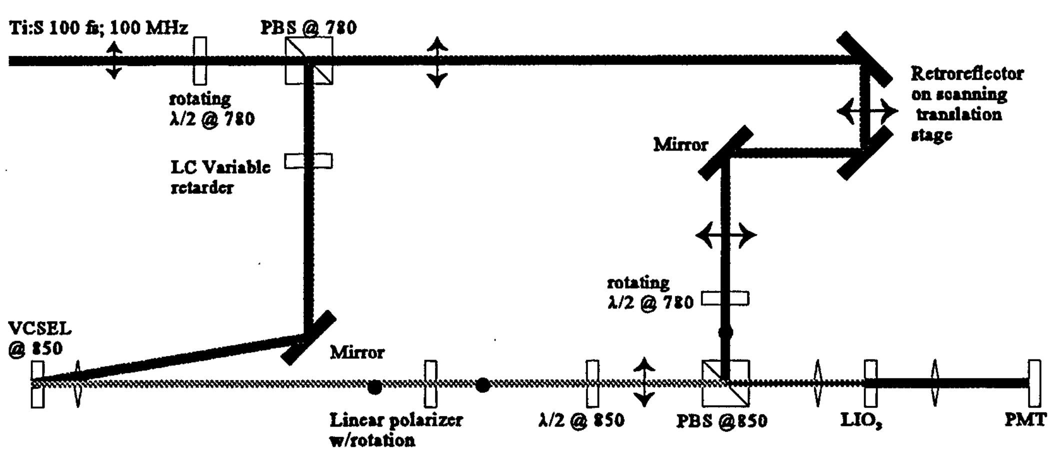
3 Theoretical Modeling (cont.)

There are great advantages to the almost-analytical solution of Maxwell's equations developed in Ref. 2, especially for the future project of developing a comprehensive microscopic model of the laser operation of VCSELs. Since the microscopic models for the nonlinear optical behavior and optical gain characteristics of the active layers require extensive numerical resources, the semi-analytical solution of the corresponding electromagnetic problem is needed to keep the problem numerically feasible. But the use and applications of the vectorial transform matrix approach does not require the targeted full microscopic model. Much information about the dependence of laser threshold and resonant wavelengths can already be obtained from the electromagnetic model alone, as discussed in Ref. 2.

4 Experimental Efforts

Femtosecond Pump-Probe System Design

The pump-probe set-up sketched schematically below was constructed to test VCSEL polarization response to polarized femtosecond pulses at 780 nm. The beamtrain was



designed to focus femtosecond pulses with controllable polarization on VCSEL devices, then time-resolve the anticipated changes in the CW VCSEL output through second-harmonic generation (SHG) in a nonlinear crystal. This is similar to the standard autocorrelation technique used to measure the width of picosecond and femtosecond-scale pulses.

The polarization of the pulses input to the VCSEL device under test was controlled by having them first traverse a Meadowlark Inc. liquid-crystal variable retarder, which allowed a desired retardance to be created between x- and y- electric field components in response to an applied electric field.

A polarizing beamsplitter/rotatable half-wave plate combination allowed a selectable fraction of the input pulses (a reference beam) to be split off and directed toward a computer-controlled delay line, which employed a corner-cube retroreflector mounted on a micron-resolution motor-driven translation stage. By moving the translation stage back and forth, a variable delay could be created between the reference pulses and the output of the VCSEL after it was struck with the polarized input pulses. Both reference and VCSEL output beams were then collinearly combined in a LIO_3 nonlinear crystal.

By scanning the delay between the two beams, the overlap between them could be adjusted so as to facilitate SHG within the nonlinear crystal. The overlap signal, which would be distinguished by being at twice the frequency of the two constituent beams, would then be a measure of the temporal shape of the VCSEL output changes induced by the polarized input signal. A sensitive photomultiplier tube, supplied with filters which would block the

fundamental signal and pass only the second harmonic, was positioned so as to detect the overlap signal. In this fashion, the desired signal from the VCSEL could be tracked as a function of delay and displayed on an oscilloscope. To resolve the polarization of this signal, a linear polarizer upstream of the LIO_3 was used, enabling scanning delay line measurements to be taken as a function of polarization angle. This scheme would then give the time- and polarization-resolved output of the VCSEL device when pumped by input pulses of varying polarization.

Characterization of Donated VCSELs

Before testing could proceed on actual VCSELs, the individual devices had to be tested and characterized. Two sets of VCSELs were donated to our effort by Vixel, Inc. of Longmont, Colorado. Initially, two wired-bonded and packaged 1 x 2 arrays of nominally 840-nm devices were sent by Vixel. They put out approximately 3 mW of optical power at an operating current of 7 mA. The center wavelength of the devices under these conditions was measured using an Oriel InstaSpec diode array/spectrometer system to be 837.5 nm. The high-reflectivity band of the VCSEL cavity mirrors, though not measured directly by our group, was stated by the manufacturer to fall off sharply at approximately the center wavelength ± 40 nm. Thus at 780 nm, where our pump beam wavelength was centered, the reflectivity was quite low, allowing efficient absorption of the pump pulses by the VCSEL. Polarization of these devices was measured with high-quality quartz polarizers to be strongly linear, with approximately 100:1 polarization purity.

Once these characteristics were determined, the devices were inserted into the set-up diagramed above, and a lengthy process of alignment began. The SHG process in nonlinear

crystals is extremely sensitive to the angular orientation of the two input beams ("phase matching") as well as to the polarization orientation with regard to the relevant crystal axes. As it turns out, SHG also requires a relatively large pulse energy to be present in both the beams to be nonlinearly combined. After many weeks of tedious alignment efforts, both of the donated VCSEL devices eventually failed without a significant upconversion signal from the VCSEL having been observed. Though some blue output characteristic of SHG was noted, this was readily determined to be simply due to doubling of the reference signal rather than the result of correlation between the VCSEL signal and the reference.

Three months later, a new set of VCSELs arrived from Vixel, Inc. These came in the form of 1 *x* 16 arrays, rather than TO-can-packaged device chips. The output apertures of these devices were even smaller than the original set (about 8 microns in diameter, rather than the 20 micron diameter of the earlier device windows.) Their output wavelengths were similar at around 840 nm, but with even lower output powers -- about 1 mW or less at the desired operating current. Polarization orientation was again strongly linear, though not identical for each device, with polarization purity of 100:1 or greater for the individual devices tested (not all of the elements of the array were functional when we received them.) The smaller output apertures and lower output optical powers of these devices made them vastly more difficult to incorporate into our testing setup, both because of the difficulty in focusing our 780 nm pump pulses down on to them (using an off-axis geometry) and because of the weak CW power available for SHG in the LIO_3 crystal.

4 **Experimental Efforts** (cont.)

Pump-Probe System Results

By the end of the original project period (Dec. 31st, 1996) Gary Vaillancourt, the lead engineer on the pump-probe system, was unable to obtain a resolveable upconversion signal from the VCSEL devices we tested. Mr. Vaillancourt attributes these results to the following possible factors:

- insufficient CW output power from the VCSELs themselves to generate nonlinear SHG in the LIO_3 we had on hand.
- Ti:Sapphire oscillator instabilities (i.e., difficulty in keeping the source of mode-locked femtosecond pulses to stay mode-locked for any length of time.)
- Significant losses encountered by the VCSEL output signal before reaching the nonlinear crystal (e.g., from the linear polarizer and polarizing beamsplitter visible in the schematic diagram of the pump-probe set-up.)

After securing a six-month extension of the grant (until June 30, 1997), it was learned that Mr. Vaillancourt's commitments at the Rome Laboratories Photonics Center and at Resonetics, Inc. would keep him from being able to further pursue the VCSEL polarization switching project without additional funding. Accordingly, we sought new collaborators who could assist in further testing of the VCSELs we had on hand. Prof. Alex Cartwright of the ECE dept. at SUNY Buffalo -- a graduate from Art Smirl's group at the University of Iowa with vast experience in ultrafast pump-probe experiments -- agreed to assist in the project at this point. We transferred our VCSEL arrays, drive electronics, and beamtrain components to his laboratory, which includes a Spectra-Physics Tsunami mode-locked femtosecond Ti:Sapphire laser. In addition, Prof. Cartwright had an existing delay-line and data

acquisition set-up in place, including a BBO-based SHG crystal which promised better upconversion efficiency of the 850 nm VCSEL output than the LIO_3 crystal we had been using.

Unfortunately, after several months of effort by Prof. Cartwright and one of his graduate students, primarily during the months of April through June of 1997, he eventually concluded, as had Mr. Vaillancourt before him, that the CW VCSEL output power was simply too small to generate the needed SHG signal. The SUNY Buffalo group's measurements indicated that approximately an order-of-magnitude increase in the VCSEL output power was necessary. This would imply VCSEL elements with approximately 10 mW of CW output at 850 nm. Such devices are not currently in commercial production, and it was thought impractical at such a late stage in the contract period (actually after the contract extension had concluded) to attempt to have custom devices fabricated.

5 Conclusions

Theoretical simulations of femtosecond nonlinear optical response in strained quantum wells, coupled to modeling of the electric field properties of VCSEL device geometries continue to provide promising evidence that VCSEL output polarization can be externally controlled on a picosecond timescale through addressing by circularly-polarized femtosecond pulses. However, experimental confirmation of these predictions has thus far been hampered by the lack of sufficient output power from commercially-available VCSELs to generate the second-harmonic upconversion signal required to time-resolve the anticipated ultrafast changes in VCSEL output polarization. Three possible approaches for further study are suggested:

5 Conclusions (cont.)

1) have individual VCSEL devices custom-designed and grown to produce CW output powers of 10 mW of more; 2) Adjust the beamtrain so as to collimate the VCSEL output with a smaller beam diameter, allowing a larger depth of focus at the nonlinear crystal for easier phase-matching; 3) pursue a technique for characterizing the polarization state of the VCSEL output on an ultrafast timescale that does not require second-harmonic generation. One possible approach is the one recently outlined by Walecki et al. at the University of Iowa, which relies on dual-channel spectral interferometry and is particularly adept at resolving weak signals[8].

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